Understanding the Structure of the Turbulent Mixing Layer in Hydrodynamic Instabilities

V. Pascucci[1,2], P. Miller[1], P.-T. Bremer[1], D. Laney[1], and A. Mascarenhas[1]
[1]Lawrence Livermore National Laboratory; [2]University of California, Davis

Summary

When a heavy fluid is placed above a light fluid, tiny vertical perturbations in the interface create a characteristic structure of rising bubbles and falling spikes known as Rayleigh-Taylor instability. Rayleigh-Taylor instabilities have received much attention over the past half-century because of their importance in understanding many natural and man-made phenomena, ranging from the rate of formation of heavy elements in supernovae to the design of capsules for Inertial Confinement Fusion. We have developed a new approach to analyze Rayleigh-Taylor instabilities in which we extract a hierarchical segmentation of the mixing envelope surface to identify bubbles and analyze analogous segmentations of fields on the original interface plane. This approach is based on a family of robust topological techniques developed that allow computing multi-scale segmentation of scientific for feature extraction and error bounded quantitative analysis.

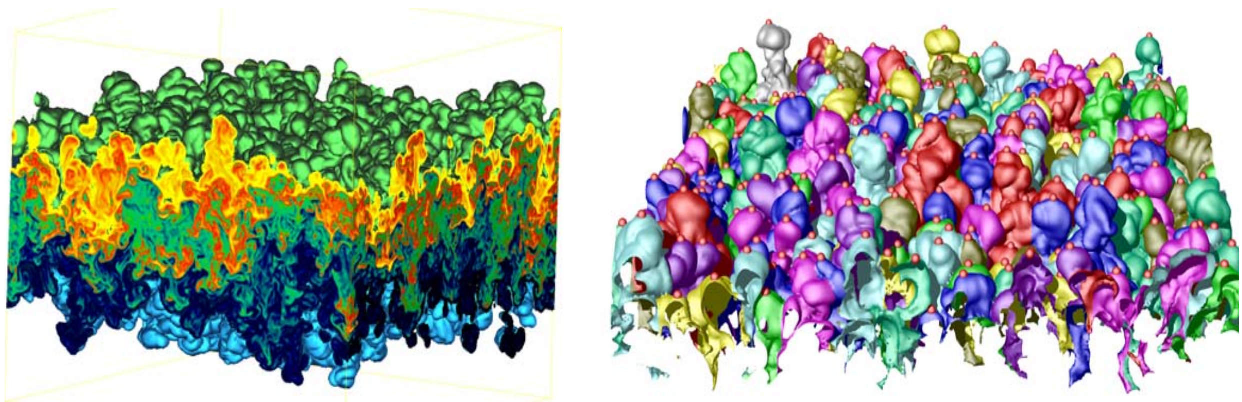

Figure 1. (left) Turbulent mixing interface of a Rayleigh-Taylor instability simulation. (right) Topological segmentation of the upper envelope highlighting in different colors the bubbles that rise during the mixing process.

The work focuses on the robust analysis of Rayleigh-Taylor instabilities, which are created when a heavy fluid is placed above a light fluid and tiny vertical perturbations in the interface create a characteristic structure of rising bubbles and falling spikes. Rayleigh-Taylor instabilities have received much attention over the past half-century because of their importance in understanding many natural and man-made phenomena, ranging from the rate of formation of heavy elements in supernovae to the design of capsules for Inertial Confinement Fusion.

To overcome the challenge of analyzing the complex topology of the Rayleigh-Taylor mixing layer we have developed a novel approach based on robust Morse theoretical techniques. This approach segments systematically the envelope of the mixing interface into bubble structures (Figure 1) and represents them with a new multi-resolution model allowing for the first time a multi scale quantitative analysis of the rate of mixing based on bubble count. The analysis highlighted and provided precise measures for four fundamental stages in the turbulent mixing process that previously scientists could only observe qualitatively, therefore enabling new insights and deeper understanding in this fundamental phenomenon (Figure 2).

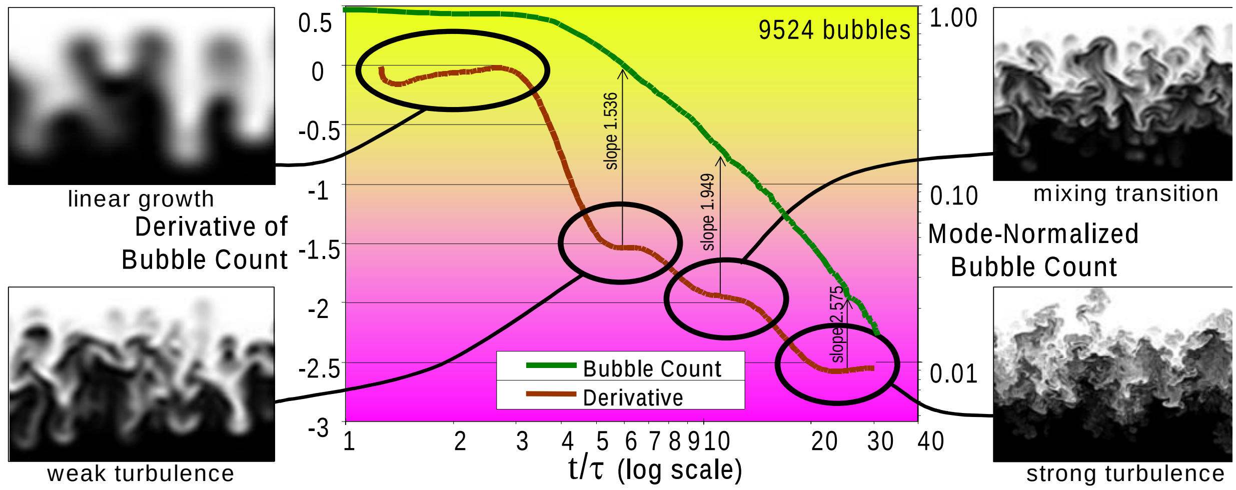

Figure 2. Time analysis of the bubble structures in the Rayleigh-Taylor mixing interface. Our approach both highlights qualitatively the four main stages of the process and quantifies the mixing rates characterizing each stage.

This work has been documented in a paper winner of the "Best Application Paper" award at the IEEE Visualization Conference [1] and later presented at International Workshop on the Physics of Compressible Turbulent Mixing [2]. Follow-up work allowed also for the first time direct comparison two simulations based on different physics models and run with different initial conditions; the first run with 1 billion nodes over 758 time steps, the second run with 27 billion nodes over 220 time steps. Although comparison by superposition of the two simulations could not yield any meaningful result, the topological approach allowed a multi scale feature based comparison highlighting fundamental similarities (Figure 3), which validated the lower resolution large eddy simulation (LDS) with respect to the higher resolution direct numerical simulation (DNS).

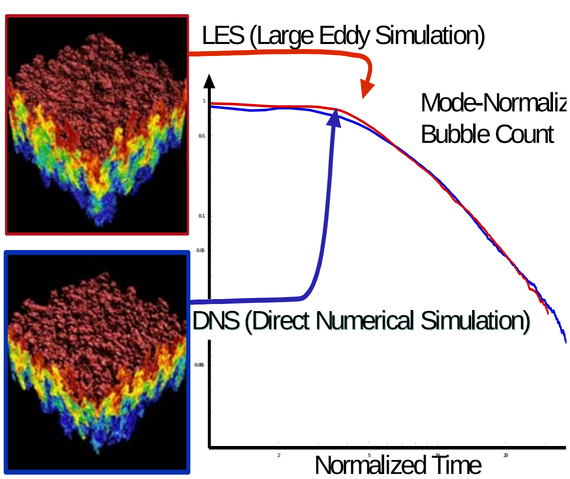

Figure 3. Feature based comparison of two Rayleigh-Taylor instability simulations based on different models and run with different initial conditions. The results validate the Large Eddy Simulation (top) with respect to the Direct Numerical Simulation (bottom).

Publications

[1] D. Laney, P.-T. Bremer, A. Mascarenhas, P. Miller, and V. Pascucci. *Understanding the structure of the turbulent mixing layer in hydrodynamic instabilities. IEEE Trans. Vis. Comput. Graph, 13(1):1053–1060, 2006*.

[2] P. Miller, P.-T. Bremer, W. Cabot, A. Cook, D. Laney, A. Mascarenhas, and V. Pascucci. *Application of morse theory to analysis of rayleigh-taylor topology. In 10th International Workshop on the Physics of Compressible Turbulent Mixing, 2007.*

For further information on this subject contact:

Name: Valerio Pascucci.
Organization: Lawrence Livermore National Laboratory.
Email: pascucci@llnl.gov
Phone: (925) 423-9422

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